

PATENT SPECIFICATION

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DRAWINGS ATTACHED

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(54) IMPROVEMENTS IN OR RELATING TO PROTECTION OF STRUCTURAL PARTS FROM ABRASION

- (71) We, NATIONAL RESEARCH CORPORATION, a Massachusetts Corporation, United States of America, of 70, Memorial Drive, Cambridge, Massachusetts, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—
- 10 The present invention relates to component structural parts used in aerodynamic environments such as ground based and airborne compressors (including rotor blades and stator vanes and structural ribs and inlet mouth) and
- 15 other aircraft air breathing lip portions such as turbofan blades and nacelles. Typical of such parts is the compressor rotor blade used in the turbocompressor engines which drive helicopters and/or provide auxiliary power
- 20 thereto. Such blades can be made of such metals as elemental titanium or titanium high strength alloys (e.g. Ti—6Al—4V; Ti—4.5Al—12Zr; Ti—7Al—4Mo; Ti—4Al—3Mo—1V; Ti—5Al—2.5Sn; Ti—6Al—2Sn—4Zr—2Mo;
- 25 and other titanium alloys whose strength exceeds that of elemental titanium at low temperatures); aluminum high strength alloys; and 403, AM355 and Inco 718 stainless steel (“Inco” is a Registered Trade Mark). The
- 30 blades are of high strength but vulnerable to erosion. In order to extend the service life of aircraft powerplants using such blades, the blades are coated with a hard, ceramic coating.
- 35 Extensive operation of military aircraft in southeast Asia has brought to the foreground the extent of the erosion problem. A broad test review of various combinations of compressor blade materials and coatings to
- optimize erosion resistance is set forth in an article by Bergman and Bartocci/General Electric Company, entitled “Erosion Tests of Compressor Alloys and Coatings for Aircraft Gas Turbines” presented at the Eighth Annual National Conference on Environmental Effects on Aircraft and Propulsion Systems (1968; proceedings published in Institute of Environmental Science, 940 E. Northwest Highway, Mount Prospect, Illinois 60056) pp. 137—142.
- 50 The present invention has application to the above problem area and also has application to the following problem areas:
- (1) compressor and fan blades (including movable blades and fixed vanes or blades), generally, and fixed inlet ribs and leading
- 55 adges;
- (2) low flying aircraft and high speed ground and water vehicle leading edges;
- (3) wind tunnels
- 60 all of which through motion or suction can produce an aerodynamic environment under conditions of severe impact abrasion. Also included are:
- (4) objects in the path of an aerodynamic
- 65 environment produced by an exhaust stream or wake such as aircraft fairings impinged by dust, kicked up by wheels or thrust deflectors and reversers upon
- 70 landing, racing cars, tractors, trucks, airport runway and rocket launch site exhaust deflectors.
- The parts noted above are “structural parts” of the compressor aircraft and have “surface portions” exposed to the aerodynamic environment under conditions of severe impact
- 75 abrasion. Another common characteristic of the above described structural parts is that they are made of what may be termed “low temperature strength materials”. That is, they
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[Price 25p]

are designed for operation under conditions where their temperatures do not reach above degradation temperature, e.g. 1000°F (538°C) for stainless steels and titanium alloys or above about 200 or 400°C for plastic matrix composites or aluminum, respectively, for sustained periods. Final fabrication operations on such parts are similarly limited. This class of materials obviously includes metals and also includes non-metals such as the glassfiber-reinforced plastic composites or boron or carbon fiber reinforced matrix (plastic or metal) composites. Such materials, as a result of composition and construction and/or fabrication history have high strengths which would be degraded if heated above their "softening", "recovery" or "aging" temperature in the case of metals or "dissociation" temperature in the case of plastics or reinforced plastics and generically expressed as "degradation temperature" here. It is also desirable to hold temperature of fabrication even lower in the case of metal parts to minimize grain growth and changes of endurance limit and in the case of composites to limit interfacial diffusion or reaction between substrate and matrix and/or impurities therein.

The erosion protection problem is intimately involved with the low-temperature-strength character of the materials used in such structural parts. Good erosion resistant coatings of titanium carbide with high adhesion can be applied to the parts with high adhesion by chemical vapor deposition. But the present state of the art limits use of chemical vapor deposition because the parts must be held at temperatures above degradation temperature during the coating process. Research is now in progress to achieve lower temperature chemical vapor deposition.

It is the object of the invention to provide such structural parts with improved erosion resistance without significantly degrading the strength thereof.

In general the object is achieved through producing such parts with vacuum deposited coating of boron carbide. In order to obtain adherent boron carbide coatings of adequate thickness, the parts are heated during deposition. But it is feasible to accomplish deposition of thick coatings at temperatures below the degradation temperatures of the products involved. In particular several metal and composite parts in the nature of flat panels and compressor blades or inlet ribs have been coated with boron carbide with the part held at about 400—500°C. Good adhesion of thick coatings (.3 mil or greater in thickness and up to 2.2 mils) has been obtained. The coatings have improved the erosion resistance of the parts. The coating temperatures are consistent with the low temperature strength character of materials in the parts and the coating process does not degrade strength. The boron carbide coatings, per se, have the amorphous (including

micro-crystalline, i.e. crystal size, if any, less than 100 Angstroms) structure characteristic of "low temperature" deposits.

The invention generally described above includes, inter alia, two distinct species.

One species involves direct application of the coating to the surface portion of the structural part which is exposed to aerodynamic environment under conditions of impact abrasion. The surface portion may be pre-treated prior to coating as by cleaning and/or application of an undercoat to enhance adhesion of the boron carbide coating.

The second species involves applying the boron carbide to an intermediate substrate such as a thin metal foil and adhering the coated foil to the surface portion of the structural part subject to aerodynamic environment under conditions of impact abrasion. Any heating to accomplish adhesion must be below the degradation temperatures of the part and the film. The intermediate substrate may be pre-treated prior to coating as by cleaning and/or application of an undercoat to enhance application of a boron carbide coating.

Degradation is indicated indirectly by substantial change in substrate microstructure including (for metals) grain growth and growth of precipitates. Substantial change is quite clear for purposes of relative comparison. To pin it down for absolute measurement, it comprises a two-fold growth for visible grains or precipitates or a change from invisible to visible at a given level of magnification.

Other objects, features, advantages and species of the present invention will in part be obvious and will in part be stated in the following specific description which is made with reference to the accompanying drawings wherein:

FIG. 1 is a schematic diagram of a vacuum coating system used to coat parts,

FIG. 1A is a schematic cross section view of a coated product according to a first embodiment of the invention.

FIGS. 2, 2A and 2B are a schematic cross section view of a coated and laminated product according to a second species of the invention.

FIG. 3 is a cross section of a generalized impact problem met by a coated part.

Referring now to FIG. 1 there is shown a coating apparatus comprising a vacuum chamber 10, a source 12 of coating vapor V, containing a solid charge 14 of boron carbide which is melted and vaporized—by impacting electrons emitted from an electron gun 16—to produce vapor V streaming towards a substrate part, e.g. a compressor blade, 20. The substrate part is held by a jig 22 which may optionally be rotated by a motor to provide complete exposure of the substrate surface to impinging coating vapors V. The substrate can be protected by a movable shutter 26. The substrate can be heated during deposition by

a heater 28. The chamber pressure is controlled by a vacuum pumping system 30 including the usual rough pumping, high vacuum pumping, measurement and air release controls.

- 5 During the coating process typical conditions are background pressure of about 10^{-5} to 10^{-4} torr, substrate temperature of 530°C (for a titanium substrate), electron gun power input of 6 kilowatts, vapors V impinging on the substrate condense and build up coating at a rate of about $20,000\text{\AA}$ per minute (350\AA per second; this high rate is desirable to minimize disproportionation of B_4C compound). A typical coated part 200 is shown in FIG. 1A. The part is a titanium compressor blade 20 conformed for movement in the direction M when mounted in a compressor. It is coated around its leading edge, concave side and tail with a coating of boron carbide approximately 1 mil thick throughout except for grading at the edges of the coating. The 'around-the-corner' coating can be achieved by rocking the substrate part during coating. The remaining uncoated area can be covered by such conventional coatings as nickel plate, epoxy or urethane or left bare or coated with a thinner layer of boron carbide.

- 25 The basic protection provided by the vacuum deposited boron carbide coating is against erosion-producing microparticle impact as discussed above. But a high degree of protection against impact of gross foreign objects is also afforded by thick coatings at the leading edge of blades and vanes and on concave sides of first stage blades.

- 30 Another significant form of protection afforded by the vacuum deposited boron carbide coating is corrosion protection. To utilize this feature, the coating should be applied all around the substrate part. The most interesting point regarding corrosion is that the vacuum deposited boron carbide applied to the common materials utilized for low temperature aerodynamic use displays little galvanic activity therewith. This is in contrast to some other potentially competitive erosion protection coating systems which can protect against corrosion but once corrosion begins tend to drastically accelerate its rate through galvanic action. The improvement afforded by the present invention is due partly to the electrochemical and chemical inertness of boron carbide with respect to the class of substrates described here and the low porosity of the coating as applied through the vacuum deposition process described herein. Good adhesion also plays an important role.

- 55 FIG. 2 shows a second species of the invention wherein the boron carbide coating 201 is applied to an intermediate substrate 202 such as a 2 mil thick aluminum, titanium or plastic foil to form a coated article 203 which is laminated to a structural panel 204, e.g. a glassfiber reinforced epoxy airplane fairing section, by an adhesive or braze layer 205. The coated product 203 would be flexible

enough to bend around and conform to a curving surface of panel 204. In coating foil 202 of FIG. 2 or substrate 20 of FIG. 1, the surface can be prepared by conventional preparation techniques such as cleaning and/or deposition of a suitable underlayer prior to the main coating to enhance adhesion.

FIG. 2A shows an embodiment wherein the boron carbide coating 201' is applied to an intermediate substrate 202' which is very rigid, e.g. $\frac{1}{4}$ inch thick metal, but is preshaped to conform to a wing leading edge 204' and be adhered thereto by an adhesive or braze 205'. The balance 206 of the part surface can be covered by a similar coating, alternate coating or left bare.

FIG. 2B shows an intermediate substrate 202'', e.g. $\frac{1}{4}$ mil polyimide film with boron carbide coating 201'' vacuum deposited on both sides to form a total coating laminated to substrate 204 via bonding layer 205.

FIG. 3 shows a generalized coating-erosion problem with S representing the substrate to be protected, C representing the coating and P representing impinging particles. The angle of incidence of particles may be high (frontal or about 90°), grazing (about 20°) or intermediate (about 45°). Where the coating C is very thin and a substrate soft, an impinging particle may elastically deform the coating as indicated by the dashed lines D. Increased thickness of a hard coating may avoid deformation but may be vulnerable to shattering. It also appears that a rough surface is more vulnerable to erosion than a smooth one as impinging particles chip away high points to invade the lesser coating thickness at a low point of surface roughness. Valleys in an irregular surface also tend to entrap impacting particles and prevent grazing incidence and/or rebound. Similarly a porous coating is vulnerable since it approaches the situations of thin coatings (portions of a thick coating between pores) and has an internally irregular surface. The size problem typically involves a 2 mil sand particle.

The vacuum deposited boron carbide coatings of the present invention are inherently smoother and less porous than (a) sprayed on coatings to a high degree and (b) some chemical vapor deposition coatings to a lesser degree. A further advantage is that the vacuum deposited coating lends itself to the formation of multi-layer coatings with many interfaces between layers. Experience in ballistics technology yields the suggestion that multi-layer coatings may offer improved erosion resistance in products of the class described here. One approach to production of multiple interfaces was indicated with respect to FIG. 2B above wherein the coating foil 203'' contained two layers of coating. The interfaces can be increased by laminating more of such coated foils onto the same product. Going back to the direct coated product of FIG. 1A, alternate

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spatter
or
spray

layers of material can be deposited in the same coating—either multi-layers of the same boron carbide with cooling after deposition or bleeding in reactive gas to passivate the fresh surface of each layer or by depositing alternating layers of boron carbide and a second material, e.g. aluminum or titanium. The same approach could be used in preparing a multi-layer ceramic coating on a rigid intermediate substrate for use in the FIG. 2A type of laminate construction.

Whether the boron carbide coating is applied as a single layer or as multiple layers directly or indirectly (first or second species) each layer should have a thickness of at least .5 mils (.0005 inches) and preferably over 1 mil for direct coating and 0.3 mils (.0003 inches) for indirect coating and no greater than 2 mils (.002 inches) and preferably no greater than 1.5 mil for direct coating and no greater than one-half intermediate substrate thickness for indirect coating limit adhesion problems and the aggregate of multiple boron carbide layers should be no greater than 10 mils thick, with the aggregate of boron carbide and an alternating material being no greater than 20 mils thick to avoid substituting the bulk mechanical properties of the coating(s) for those of the substrate and to limit geometrical modification of the aerodynamic surface being protected. Within these ranges optimums can be set for different substrate parts. For instance a very hard substrate requires less thickness than softer substrates.

In regard to erosion protection surface smoothness is highly important and surface roughness of the boron carbide coating or each boron carbide coating layer in a multi-layer coating should be no greater than 250 micro-inches r.m.s. and preferably no greater than 50 micro-inches r.m.s.

The present invention also comprises the subcombination of a sheet including flexible and rigid forms which can be laminated to surface areas of parts to be protected. The rigid forms can be flat or curved as necessary to conform and be laminated to the component to be protected. The sheet may be a single layer sheet or a multi-layer sheet with multiple layers formed by multiple coating steps or by laminating multiple coated substrates. The individual substrate element(s) can be coated with vacuum deposited boron carbide on one or both sides. As stated above with respect to the full combination, this subcombination part should have each boron carbide layer in a thickness of at least .2 mils and no greater than 2 mils or one-half of intermediate substrate thickness with the aggregate thickness of all boron carbide layers (if more than one) being less than 10 mils and the aggregate thickness of the sheet being less than 20 mils thick. The sheet product requires means for

bonding it to the part to be protected such as an epoxy resin which may be applied at the time of adhesion or may be applied in precursor form to the surface of the sheet for later curing at the time of adhesion. The approach of this second species would have particular utility in making field repairs and is in any cases particularly useful for large parts to be protected. For very small parts, the direct coating approach is more suitable.

EXAMPLE 1

Substrate test panels made of (a) 2024 aluminum alloy, (b) AM355 steel, (c) laminated boron fiber reinforced aluminum tape were cleaned by vapor blasting with a slurry of -325 mesh. Novallone abrasive in water to remove all outward signs of metallurgical processing such as lubricant oil stains and produce a dull surface texture. Additionally substrate (b) was sand blasted prior to vapor blasting. The substrates were stored in acetone between cleaning and installation into a coating chamber.

The substrates were put into a coater as described generally with respect to FIG. 1 above.

The samples were preheated by the substrate heater to 410°C and the crucible charged with boron carbide was melted into a large pool extending almost to the walls of the crucible. The large area melting was accomplished by deflecting the electron beam across the surface of the boron carbide charge over two degrees of freedom. The charge was commercial grade of boron carbide in the form of chunks of sand blast nozzles melted down in the crucible along with remelting of residual boron carbide from previous charges.

After melting the charge and preheating the substrate the shutter was moved aside to allow coating of the substrates by vapors emanating from the molten charge of boron carbide. Coating was carried out for 6½ minutes with the substrates heated to 410°C. In this particular run electron beam current was briefly interrupted by a blown fuse which was immediately replaced.

The thickness of the coatings samples was determined by before and after weight measurements of the substrates as being from .570—.603 mils. The coating adhesion appeared excellent on all samples. The coated 2024 aluminum samples had a superficial surface pattern which was cracked like a dried creek bottom. The other coated substrates had smooth coating surfaces.

EXAMPLE 2

A number of compressor blades were direct coated under conditions and with results indicated below:

Small roughness of BC coating

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Blade Material	Precleaning	Coating Temp. (°C)	Results
(a) AM355	acetone rinse followed by acid dip (25% HNO ₃) at 150°F	820°C	Coating failed Scotch tape test
(b) Ti-6-4	acetone rinse followed by 15 second dip in 2% (by weight) HF-6% HNO ₃ -92% H ₂ O — followed by distilled water rinse	530	Good adhesion as indicated by visual examination, handling, but discolored at edges
(c) Ti-6-4	polished by 600 grit paper — dip in 2HF-6HCL — 92 H ₂ O — rinse	530 (slow cool after coat)	Good adhesion, but discolored at edges
(d) Ti-6-4	600 grit polish, 2HF-6HNO ₃ — 92 H ₂ O dip	565	Good adhesion, scotch tape test tried and passed
(e) 403	polished with 240 grit paper, then with 600 grit, then acetone rinsed	530	Good adhesion, no discolor. Thickness of .5 mil as determined by coating flat panels in same run and weighing panels

5 Blade (d) was wobbed during coating to apply the coating to its concave face and around the corners of its edges. Blade (e) was rotated 360° at 120 revolutions per minute for all-round coating.

EXAMPLE 3

10 A series of 3/32 to 1/8 inch thick test panels were direct coated under the conditions and with the results indicated in Table 1 below. The results include testing in a Jet Abrader Tester of the type utilized for data in the article by Bergman and Bartocci referred to hereinabove and entitled "Erosion Tests of Compressor Alloys and Coatings for Aircraft Gas Turbines."

15 In Table 1, there are 11 samples, the first column indicates the material of the substrate panel: in (1)-(4) the alloy of titanium-aluminum-vanadium commonly known as

Ti-6-4, in (5)-(7) #403 stainless steel; and in (8)-(11) a composite of boron fibers in an aluminum matrix. The second column shows approximate substrate temperatures during coating. The third column is coating thickness in inches as determined by weight measurements. In some cases the thickness is followed by a parenthetical number actually used for erosion number calculations. The fourth column indicates either S for a smooth coating or I for an irregular or spotty coating. The last three columns indicate erosion number—seconds to erode one mil as calculated from actual erosion thickness reductions achieved at impact angles of 20, 45 and 90 degrees in the Jet Abrader Tester.

All the samples were direct coated by electron beam evaporation of boron carbide as in the previous examples. The samples were cleaned prior to coating as follows:

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TABLE I

Coatings and Jet Abrasion Test Results for Example 3

Base	Substrate Temp.	Coating Thickness	Comment	Erosion Number		
				at 20°	at 45°	at 90°
1) Ti—6—4	500°C	.0009 in.	S	3660 3660	675 540	600
2) Ti—6—4	530	.0003	I	146 166	100 95	36 30
3) Ti—6—4	530	.00055	I	1500 1500	900 675	235 223
4) Ti—6—4	530	.00075	S	1500 1225	2700 1350	350 340
5) 403SS	530	.0003	I	228 333	135 135	40 39
6) 403SS	530	.00053 (.00055)	S	3660 3660	2700 1350	286 270
7) 403SS	530	.00053 (.00055)	S	3660 3660	2700 2700	340 365
8) Fiber Composite Al/B	400	.00048 (.00055)	S	1000 600	270 250	93 86
9) Fiber Composite Al/B	400	.00048 (.00055)	S	97 130	250 278	103 92
10) Fiber Composite Al/B	400	.00025	S	92 78	40 50	10 10
11) Fiber Composite Al/B	400	.00022 (.00025)	S	85 93	40 40	10 10

EXAMPLE 4

Two composite panel substrates were indirectly coated. The composites were epoxy matrix-carbon fiber reinforced. The intermediate substrate in one case was 0.25 mil polyimide film coated with 0.2 mils B₄C on one side and 0.1 mil B₄C on the other side. This did not give a significant improvement in erosion performance (erosion number of 5 at 90°, 15 at 45°).

In the second case a 2 mil aluminum foil was used as the intermediate substrate. It was coated in a continuous coating machine as described in the paper by Beecher et al entitled "Laminar Film Reinforcements For Structural Applications", paper NR—3 at the 12th National Symposium of the Society of Aero-

space Mechanical and Process Engineers, Proceeding published 1968. It was heated to about 400°C during coating and had .36 mils thick boron carbide on one side. Three such strips were laminated with the composite substrate.

The lamination of the aluminum foil was carried out using two mixtures of adhesive. A first mixture (A) comprised 6.5 grams ERL2256 epoxy resin, 1.3 gm "Z" catalyst, 2 drops Z6020 silane coupling agent in 162.5 gm methylethyl ketone solvent. The second mixture (B) was solventless and comprised 45.8 gram of the epoxy, 9.2 gm catalyst Z, 0.2 gm silane. The substrate strip was cleaned in a bath of warm trichloroethylene (TCE) and brushed lightly, then removed from the bath

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and sprayed with TCE. This was repeated and then the part was sprayed with acetone, then ethyl alcohol. The substrate composite was cut out of a larger piece into a 1.5 inch wide by 1 inch long strip, 80.3 mils thick, using a diamond cut-off grinding wheel. The coating strips were similarly cut. The substrate strip and all the coating strips were sprayed with mixture A and then heated in a 225F oven for 23 minutes to effect solvent removal and partial cure. The substrate strip with its sprayed side facing up then had a bead of mixture B put into the center of the sprayed side. (The bead was outgassed in a vacuum dessicator prior to application to remove air bubbles entrapped in mixing). Then a B₄C/Al piece was put on top of this (Al side down). A bead of mixture B was placed on the upper B₄C side. The procedure was repeated for the next two B₄C/Al layers. This layup was put in a press and heated to 225F and then pressure of 750 p.s.i. was applied. Temperature and pressure were held for 1 hour and then temperature was held for 1 hour at 300F at about the same pressure. The thickness of the total laminate was 81.6 mils average.

The second indirectly coated panel exhibited an erosion number of 50 under condition of 90° impingement and 80 for 45° impingement. It should be noted that the uncoated composite part typically exhibits an erosion number of about 3 and 90° impingement.

EXAMPLE 5

A panel of AM 355 stainless steel was direct coated to a coating thickness of 0.6 mils (.0006 inches). The coating was carried out with the substrate held at about 400°C. Prior to coating the part was pre-cleaned by vapor blasting.

The coated part when tested in the Jet Abrader Tester gave erosion numbers of 100 at 90°, 175 at 45° and 1500 at 20° impingement.

The part was also examined before and after coating to see if its microstructure had changed and no significant change in the nature of grain growth or coarsening of precipitates was noted.

Desirable variations of the Example 4 work above would include the use of B₄C coated titanium or nickel foils for lamination to substrates. Titanium and nickel make desirable erosion resistant layers per se and because of reasonably close match to B₄C (in thermal coefficient of expansion allow thicker coatings relative to substrate thickness and with high adhesion than, say, aluminum foil or plastic film.

WHAT WE CLAIM IS:—

1. An improved structural part for use in low temperature aerodynamic environments under conditions of severe impact abrasion as in compressors, fans, aircraft leading edges,

wind tunnels, automobiles, tractors, gas deflectors, aircraft fairings and the like, comprising in combination:

- (a) a low temperature strength part constituting the basic structural part and comprising a surface portion arranged for exposure to said abrasion condition, and
- (b) a vacuum deposited coating of boron carbide adhered to said surface portion, said coating having an essentially microcrystalline structure and thickness of at least 0.3 mils,

whereby erosion resistance of the structural part is increased at least two-fold without degradation of the strength of the part due to the combination.

2. The product of claim 1 wherein the coating is at least half a mil thick.

3. The product of claim 1 wherein the part is made of a titanium alloy having a room temperature strength in excess of that of elemental titanium.

4. The product of claim 1 in the form of a compressor blade.

5. The product of claim 1 wherein the boron carbide coating is directly coated on said surface portion.

6. The product of claim 5 wherein adhesion of the boron carbide coating to the surface portion is enhanced by a metallic undercoat.

7. The product of claim 5 with direct bonding of the boron carbide coating to said surface portion.

8. The product of claim 5 wherein the boron carbide coating is subdivided into multiple layers.

9. The product of claim 1 wherein the boron carbide coating is bonded to an intermediate substrate which is in turn adhered to said surface portion of the structural part.

10. The product of claim 9 wherein adhesion of the boron carbide coating to the surface portion is enhanced by a metallic undercoat.

11. The product of claim 9 with direct bonding of the boron carbide coating to said surface portion.

12. The method of claim 9 wherein the boron carbide coating is subdivided into multiple layers.

13. A method of protecting low temperature structural parts used in low temperature aerodynamic environments under conditions of severe impact abrasion as in compressors, fans, aircraft leading edges, wind tunnels, automobiles, gas deflectors, aircraft fairings and the like, comprising the step of covering a surface portion of the part subject to such abrasion with a coating of boron carbide at least 0.3 mils thick, the coating being applied directly on the part under high vacuum with the part held at a temperature below its degradation temperature but above the temperature necessary for adhesion of the coating.

14. The method of claim 13 wherein adhesion of the boron carbide coating to the sur-

face portion is enhanced by a metallic under-coat.

- 5 15. The method of claim 13 with direct bonding of the boron carbide coating to said surface portion.

16. The method of claim 13 wherein the boron carbide coating is subdivided into multiple layers with each layer being at least half a mil thick.

- 10 17. A method of protecting low temperature structural parts used in low temperature aerodynamic environments under conditions of severe impact abrasion as in compressors, fans, aircraft leading edges, wind tunnels, automobiles, gas deflectors, aircraft fairings and the like, comprising the step of covering a surface portion of the part subject to such abrasion with a coating of boron carbide at

least .03 mil thick the coating being applied by precoating an intermediate film substrate with said boron carbide in high vacuum and adhering said coated film to the part with the part held at a temperature below its degradation temperature but above the temperature necessary for adhesion.

18. A method of protecting structural parts from abrasion substantially as hereinbefore described with reference to and as illustrated in the accompanying drawings.

19. Coated structural parts when produced by the method as claimed in claim 18.

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112 Hatton Garden, London, E.C.1.
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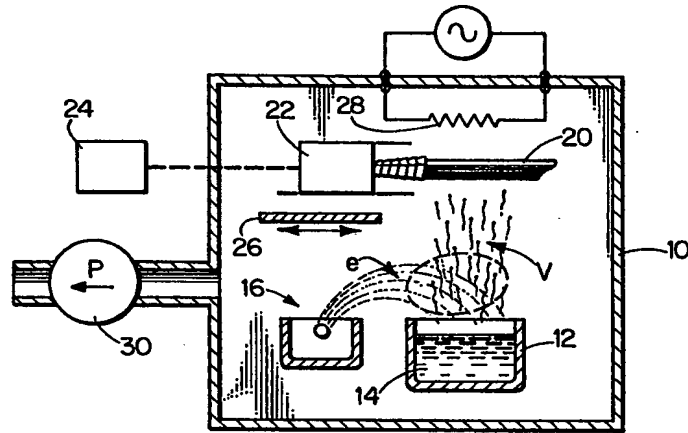


Fig. 1.

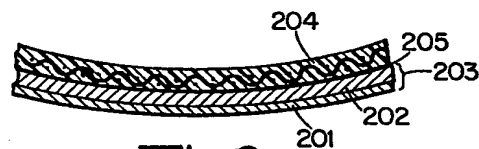


Fig. 2.

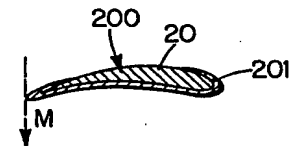


Fig. 1A.

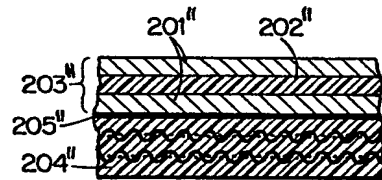


Fig. 2B.

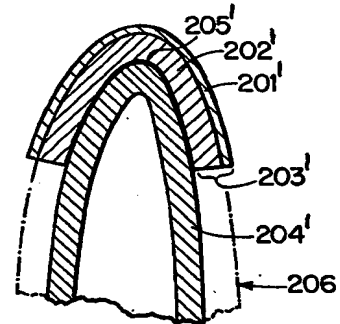


Fig. 2A.

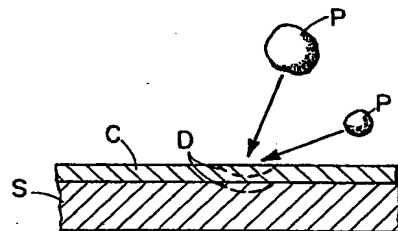


Fig. 3.

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